TESTING THE FAR UV WITH LOW-E AXION EXPERIMENTS*

*: together with P. Agrawal (OXF), M. Nee (Harvard)

based on: 2206.07053 + 2409.YYYYY

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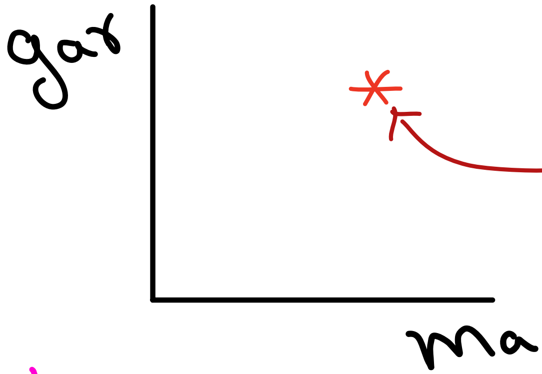
WHY TOPOLOGICAL COUPLINGS ?

Or ... what can we learn with $(g_{a\gamma}, m_a)$?



Imagine we find this tomorrow!

Dark matter ? Strong CP ?

THIS TALK!

A) Is the SM unified in the UV?

B) Can we test / distinguish different String theories at low-E?

AXION REVIEW

* Axion: periodic (compact) scalar with discrete shift-symmetry.

AKA axion-like particle (ALP)

NOT NECESSARILY COUPLED TO QCD

$$\boxed{a \to a + 2\pi f_a}$$

* Interactions shaped by shift-symmetry:

$$\frac{\partial_\mu a}{f_a} \bar{f} \gamma^\mu \gamma^5 f \; ; \quad \frac{a}{f_a} F\tilde{F} \; ; \quad V(a) = -\Lambda^4 \cos(a/f_a)$$

* Field theory language: pNGb of (anomalous) symmetries

↳ $U(1)_{PQ}$ for QCD axion

$$[SU(3)_c]^2 \times U(1)_{PQ} = \mathcal{A}_{QCD}$$

anomaly coefficient

WHY AXIONS ?

* Appear in BSM models & String Theory (i.e. AXIVERSE)
* solve strong CP problem: QCD axion
* Dark matter candidates
* Dark energy, or even inflation (?)

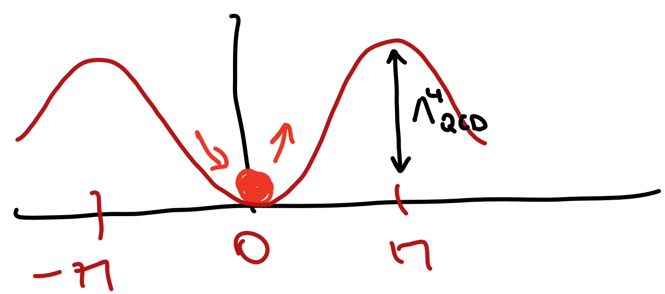
Ex: QCD AXION

$$\theta_{QCD} G\tilde{G} \longrightarrow \frac{a}{F_a} G\tilde{G}$$

* solves strong CP: $\frac{\langle a \rangle}{F_a} = 0$
* $V(a) = \Lambda^4_{QCD}\left(1-\cos\left(\frac{a}{F_a}\right)\right) \Rightarrow m_a \sim \frac{\Lambda^2_{QCD}}{F_a}$

RELIC ABUNDANCE

$$\Omega_a h^2 \simeq 0.1 \left(\frac{F_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \theta_i^2$$



WHY AXIONS - MOTIVATION

* Appear in many BSM constructions
* solve strong CP problem: QCD axion
* Dark matter candidates
* Dark energy, or even inflation (?)

* Topological, quantized couplings to gauge bosons

$$\mathcal{L}_a = \frac{(\partial a)^2}{2} + \mathcal{A} \frac{a}{F_a} \frac{\alpha_{EM}}{8\pi} F\tilde{F}$$

$\rightsquigarrow$ e.g. field strength of EM.

$\to$ QUANTISATION:

Anomaly coefficient $\quad \mathcal{A} \in \mathbb{Z}$, an integer!

TOPOLOGICAL COUPLINGS TO GAUGE BOSONS

* Anomaly coeff. unaffected by renormalization [see anomaly matching]

$$\boxed{\mathcal{A}_{UV} = \mathcal{A}_{IR}}$$

directly probing the far UV!

* "$\mathcal{A}$" unaffected by RGE but "F_a" depending on scale $\equiv$ α_{EM} "running" but e^- charge being "quantised"

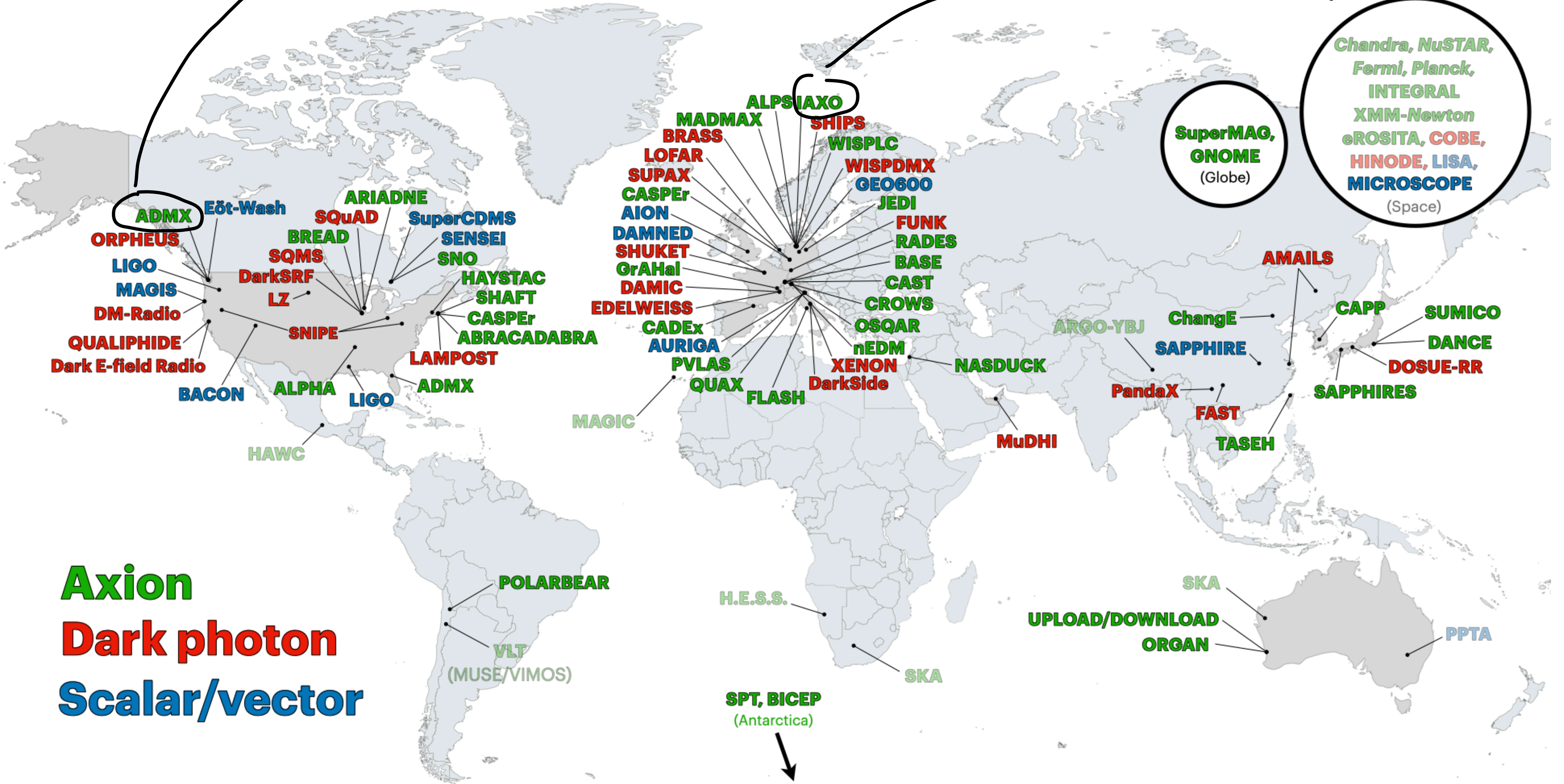
IDEA:

The axion-photon coupling is the BEST motivated channel to learn about UV physics otherwise INACCESSIBLE!

THE AXION-EXP LANDSCAPE

Haloscope: resonant cavity looking for axion DM

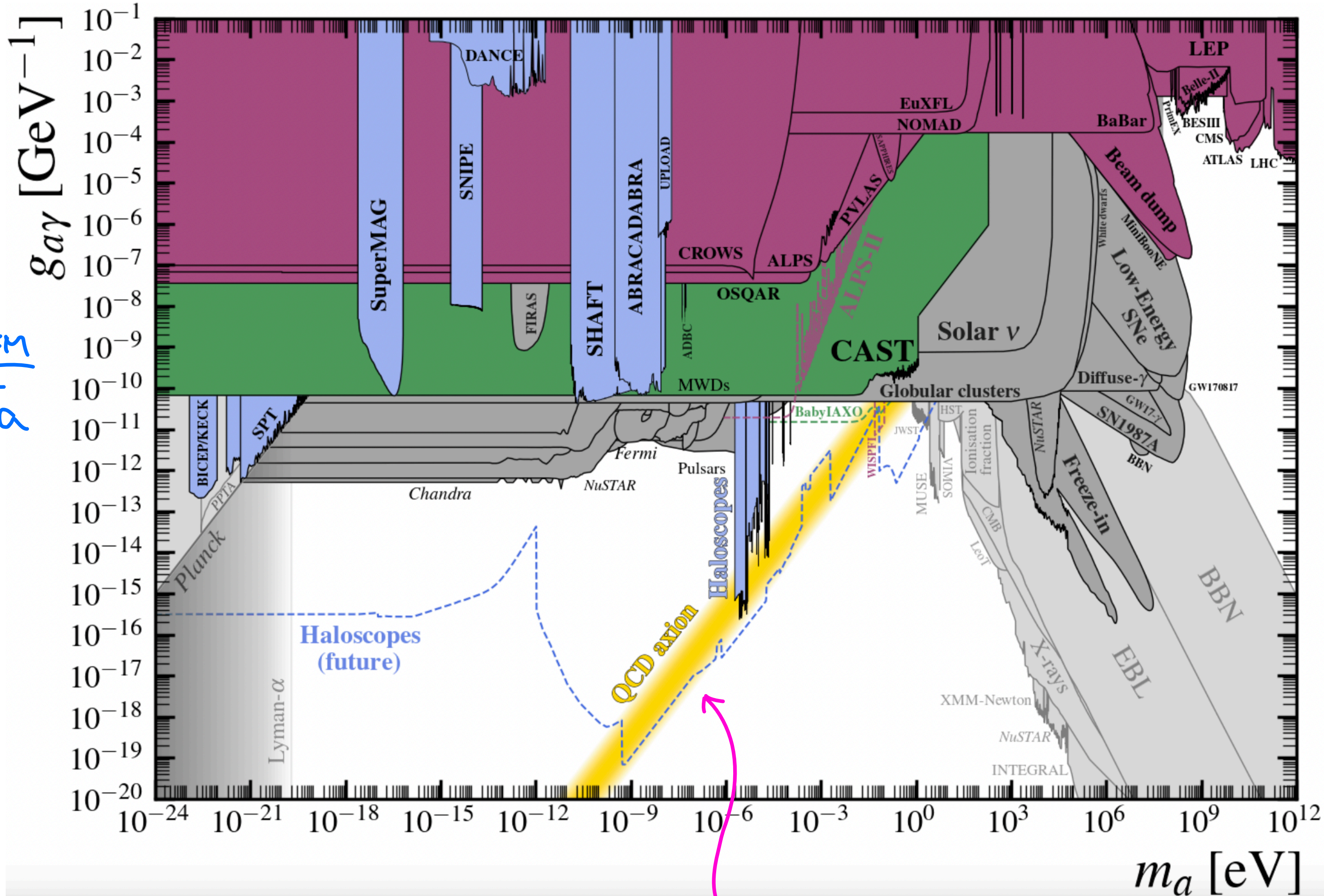
Helioscope: searches for solar axions.



THE AXION-PHOTON LANDSCAPE

many ongoing & planned searches: lab., astro., cosmo.

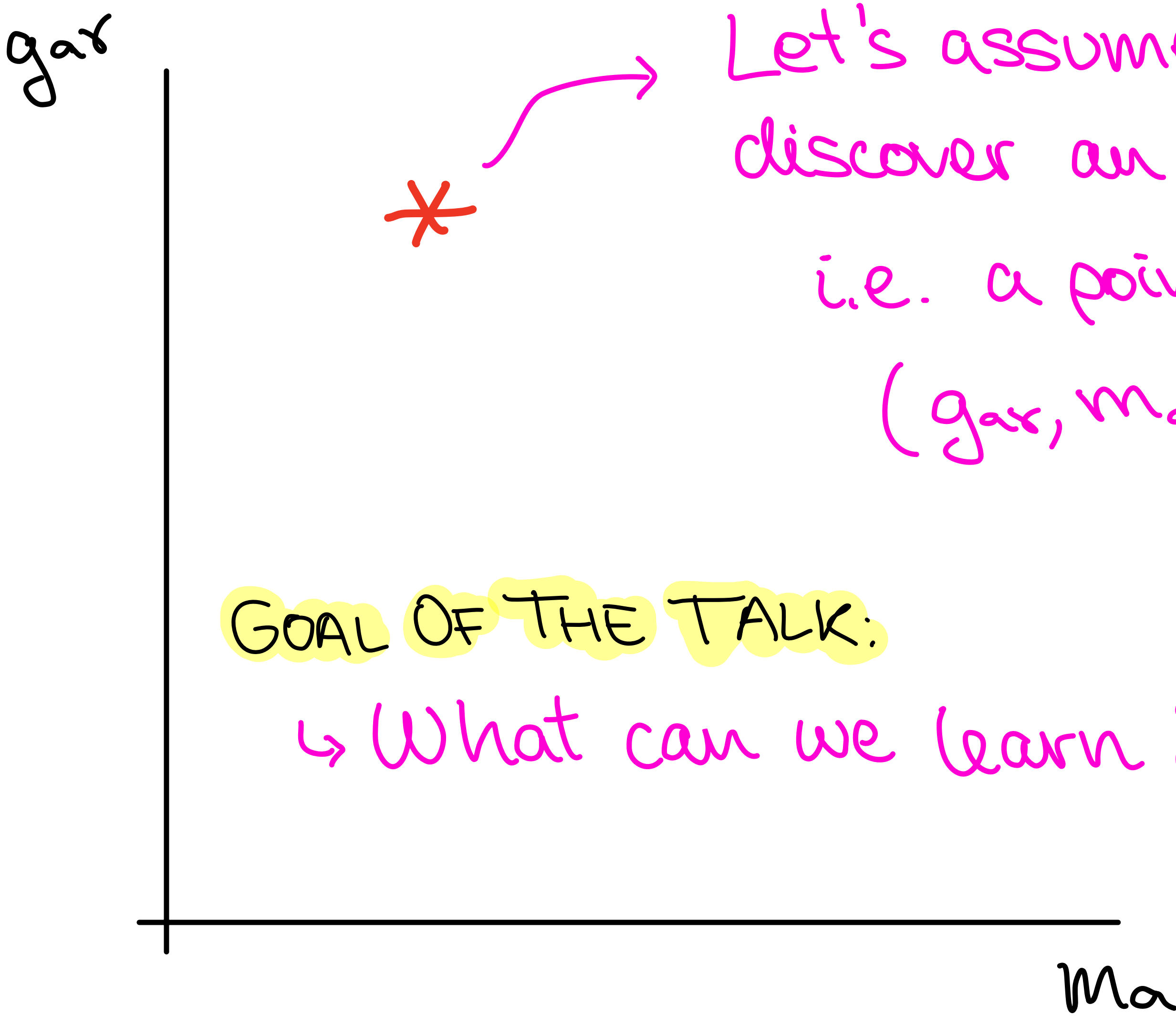
$g_{a\gamma} \sim \mathcal{A} \frac{\alpha_{EM}}{F_a}$



Ciaran O'Hare, AxionLimits

$\frac{g_{a\gamma}}{m_a} \sim \frac{\alpha_{EM}}{f_\pi m_\pi}$; QCD AXION PREDICTION

LET ME BE OPTIMISTIC!



Let's assume we discover an axion i.e. a point $(g_{a\gamma}, m_a)$

GOAL OF THE TALK:

↳ What can we learn?

APPLICATION 1

Is the SM unified in the UV?

MANY TALKS: G. Senjanovic, H.P. Nilles, M. Mondragon, H.B. Nielsen, K. Kowalsa, R. Ouyang, F. Bucella, ...

UNIFIED THEORY

$$G_{GUT} \xrightarrow{SSB} \underbrace{SU(3)}_{\text{quantum chromodyn.}} \times \underbrace{SU(2) \times U(1)}_{\text{electroweak interaction}}$$

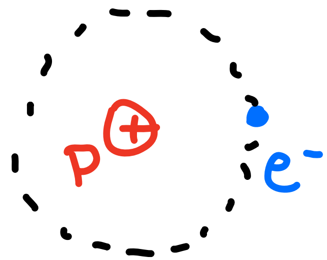
Examples
SU(5),
SO(10),
⋮

"All SM generators come from non-abelian simple gauge group"

HINTS FOR UNIFICATION

* GUTs explain charge quantisation (integers of q_{e^-})

$$\frac{|Q_p + Q_{e^-}|}{q_{e^-}} < 10^{-21}$$



Why is the H atom neutral?

* Anomaly freedom:

e.g. $\mathrm{Tr}\, Y^3 = 2\left(-\frac{1}{2}\right)^3 + 6\left(\frac{1}{6}\right)^3 + 3\left(-\frac{2}{3}\right)^3 + 3\left(\frac{1}{3}\right)^3 + 1^3 = 0$

* Unification of couplings: $\sin^2\theta_W$ & $\frac{m_b}{m_\tau}$

$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2} = \frac{3}{8} \quad , \quad \frac{m_b}{m_\tau} \simeq 3 \text{ at low E}$$

$g' = \sqrt{\frac{3}{5}}\, g_1$

Axions as Probes of Unification

[see: Agrawal, Nee, MR: 2206.07053]

Simple UV gauge group SU(5), SO(10)...

$$G_{GUT} \xrightarrow{SSB} SU(3) \times SU(2) \times U(1)$$

Axions in GUTs studied since 80s
[Wise, Georgi, Glashow, '81; Nilles, Raby; '82]

* Topological, quantised couplings to gauge bosons:

$$\mathcal{L}_a = \frac{(\partial_\mu a)^2}{2} + \mathcal{A} \frac{a}{F_a} \frac{\alpha_{GUT}}{8\pi} G\tilde{G}_{GUT}$$

* Anomaly matching: $\mathcal{A}_{UV} = \mathcal{A}_{IR}$
* Gauge invariance of G_{GUT}

Strong constraints for axion couplings!

↳ Based on topology: independent of SSB and physics @ intermediate scales

AXIONS AS PROBES OF UNIFICATION

[See: 2206.07053]

TOPOLOGY
+
GAUGE INVARIANCE

$$\mathcal{L}^{IR} = \frac{a}{f_a}\left[\alpha_{em} E F\tilde{F}_{em} + \alpha_s N G\tilde{G}_{QCD}\right]$$

anomaly coeff.

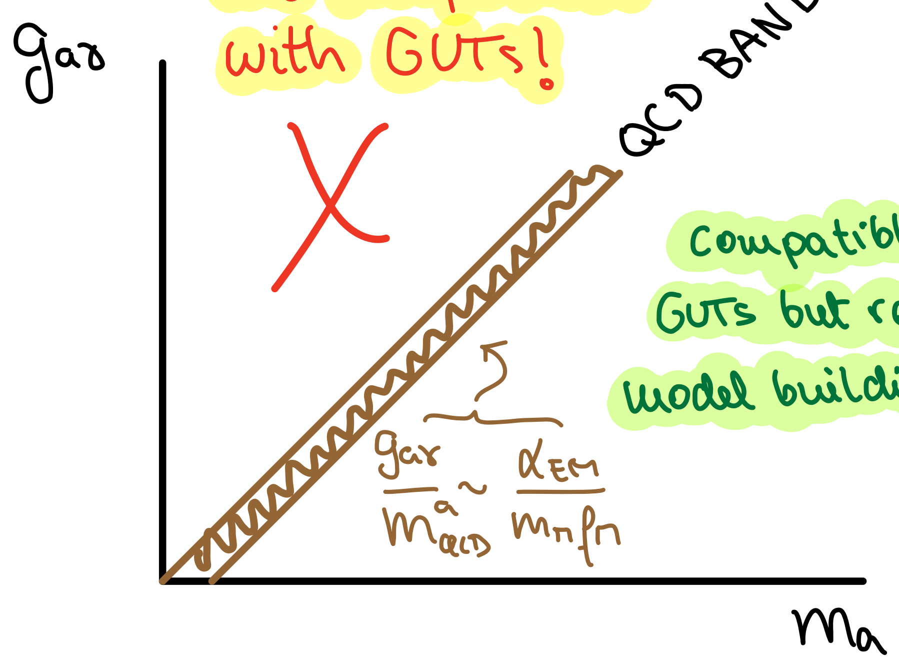
unavoidable QCD potential

$$V(a) \simeq -\Lambda^4_{QCD}\cos(a/f_a)$$

Single axion coupled to photons:

QCD axion (indep. of f_a)

not compatible with GUTs!



compatible with GUTs but requires model building!

RESULT:

$$\boxed{\frac{g^{ALP}_{a\gamma}}{m_{alp}} < \frac{g^{QCD}_{a}}{m^a_{QCD}} = \frac{\alpha_{em}}{m_\pi f_\pi}}$$

- ✱ axion mixing
- ✱ "charged axions" (pion-like fields)
- ✱ Dark photon models
- ✱ Extra dim. GUTs..

APPLICATION 2

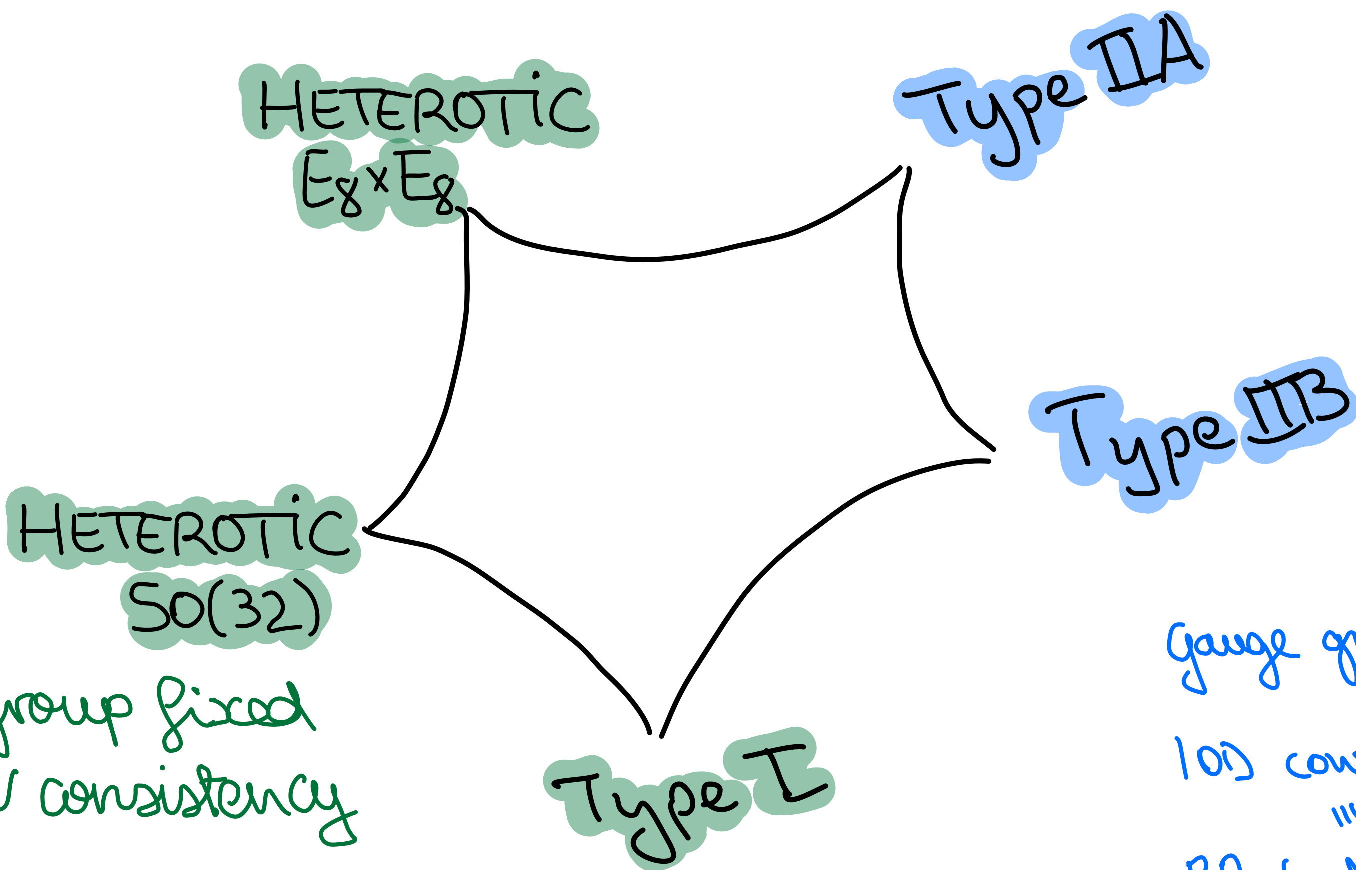
WHAT CAN AXIONS SAY ABOUT STRING THEORY ?

(or at least some of them)

Work in progress w/ P. Agrawal & M. Nee

DIFFERENT STRING THEORIES

↳ Best understood framework unifying : GR + particle physics



theories of intersecting branes!

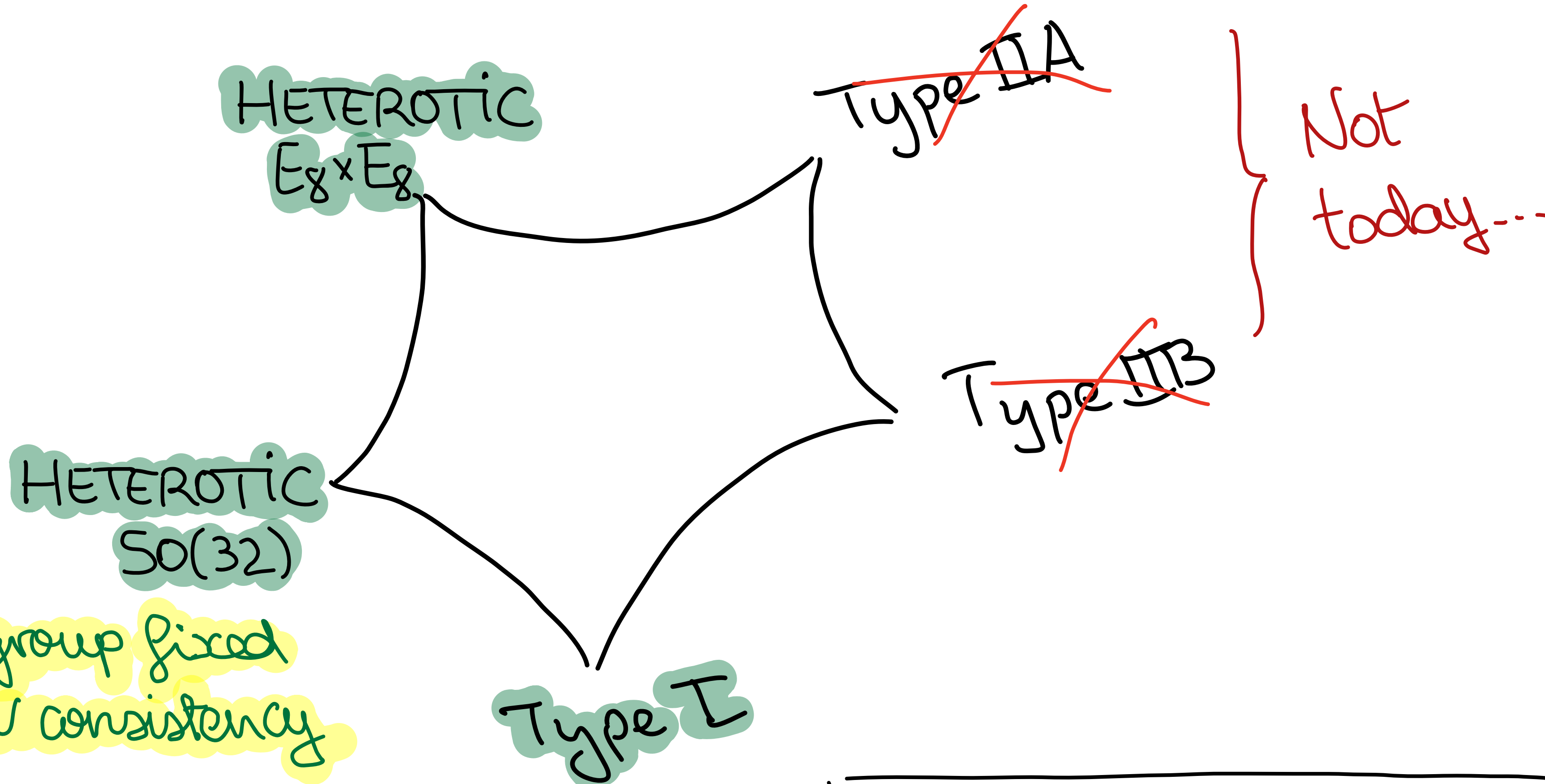
Gauge group fixed by UV consistency

gauge group may change

10D consistency
"
RR tadpole cancellation

DIFFERENT STRING THEORIES

↳ I will restrict myself to Heterotic strings...



Gauge group fixed by UV consistency

↕ 1 to 1 relation with axion couplings

→ Well defined predictions for axion-photon coupling!

STRINGY AXIONS: KNOWN RESULTS...

p-form "gauge potential"

* Multiple sources of axions in ST: B_2 , C_p , ... ~ gauge fields

"Axions from p-form fields wrapping p-cycles": $\theta_p = \int_{W_p} C_p$

* Appear in large number: # axions ~ "complexity" of compact space

STRING AXIVERSE! [Arvanitaki et al., '09]

CAVEAT! [Conlon, 0602233]

* Exponentially good PQ (moduli stabilisation might spoil this)

↳ Nicely explained by higher-form symmetries!

* Fa tends to be large! Observability? Overabundance?

[Gendler et al, 2309.13145]

See however: [Im et al. 1906.11851; Choi et al. 1104.3274; Buchbinder et al. 1412.8696] and many others...

"axiverse statistics"

WHAT'S NEW HERE?

[Huge amount of papers since Witten; Choi and Kim; et al in 80s]

i) UV consistency fixes UV gauge group in some ST

ii) Axion couplings are topological in ST: fixed at 10D level!

MATCH 10D AXION COUPLINGS $\rightsquigarrow$ 4D EFT @ R^{-1} $\rightsquigarrow$ 4D EFT @ low-E ! ADMX, or similar experiment

compactify 6D space

match couplings from R^{-1} to IR

↳ well defined axion predictions independent of details associated to: compactification & obtaining SM spectrum

$$\boxed{\text{In some ST: } g_{a\gamma}/m_a < \frac{\alpha_{em}}{2\pi}\frac{1}{f_\pi m_\pi} \text{ holds!}}$$

HETEROTIC STRINGS

* CY and toroidal orbifold compactif.

* Theory of closed (super)strings in 10D*

metric + moduli

dilaton

* Massless states: $\begin{cases} - \; g_{MN}\,,\; B_{MN}\,,\; \phi \\ - \; A_M^{ij} \end{cases}$

Gauge boson + gauginos

"charged" matter

Source of axions!

EFFECTIVE ACTION:

$\underline{S_{10}}$

10D N=1 SUGRA

* Green-Schwarz anomaly cancellation $\longrightarrow$ $E_8 \times E_8$ or $SO(32)$

Crucial for axions!

$\hookrightarrow$ e.g. $B \wedge \mathrm{tr}F^2 \wedge \mathrm{tr}F^2$

$\hookrightarrow \int_{X_6} \{\ldots\} \longrightarrow$ $a\, G\tilde{G}$

Focus on

AXION COUPLING IN 4d!

[See Svrcek, Witten for a review]

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HETEROTIC STRINGS

"Problem"? $\boxed{\text{UV simplicity vs IR complexity}}$

$E_8 \times E_8$ in 10d

↳ compactifying on Calabi-Yau or toroidal orbifold

(compact spaces with different topological properties)

+

(discrete) Wilson lines

* MANY 4D EFT become available!

Examples: SU(5), SO(10), E_6, trinification, etc...

CONNECTING FAR UV TO IR

$$S_{10} = \int d^{10}x \, e^{-\phi}\left[\sqrt{-g}R + (d\phi)^2 - |H|^2 - \mathrm{tr}|F|^2\right] + S_{GS}$$

Energy scale

Fully fledged ST

M_P

10D SUGRA
$E_8 \times E_8$

4D EFT @ R^{-1}

↳ E_6, $SO(10)$, $SU(5) \times U(1)$
$SU(5)$, Pati-Salam, SM-like ...

↳ chiral fermions depend on topology of compact space ...

LHC

EWSB

Axion Experiment

Axions offer pristine window into UV physics!

Independent of intermediate scale physics!

Results will only depend on SM embedding into $E_8 \times E_8$

Stringy Axions:

How do they look like?

AXIONS IN HETEROTIC STRINGS

[see Svrcek, Witten for a review]

↳ B_2: 2-index antisym. tensor ↳ $B_6 \equiv$ 10d dual of B_2

$$B_2 \to B_2 + d\Lambda_1$$

* Model-independent axion (a): (MI) $a = \int_{X_6} B_6$

6-form integrated over 6d space ⟶ 0-form in 4d EFT

$X_6 \equiv$ 6d compact space

* Model-dependent axions (b_i): zero modes of B_2 wrapping 2-cycles (W_i) (MD) $b_i = \int_{W_i} B_2$

↳ along "internal dimensions"

* Field theoretic axions: $\phi = \bar{\phi}\, e^{i c(x)}$ ⟶ complex phase

↳ Relevant in scenarios with anomalous U(1). Do not add new ingredients wrt MI, MD.

After dim. reduction ...

4d AXION COUPLINGS

* MI axion couplings (a): $\mathcal{L}^{4d}_{MI} = a/f_a\left(\mathrm{tr}_1 F^2 + \mathrm{tr}_2 F^2\right)$ universally coupled to gauge bosons

$\mathrm{tr}_1 F^2 = \sum_i \mathrm{tr}\, F_i^2$ ← unbroken 4d gauge groups from 1st E_8

* MD axion couplings (b_i): $\mathcal{L}^{4d}_{MD} = \sum k_i^{(1)} b_i \,\mathrm{tr}_1 F^2 + \sum k_i^{(2)} b_i \,\mathrm{tr}_2 F^2$

depend on compact space

CALCULABLE!

[see Choi, Kim in '80s]

CRUCIAL POINT: Only 2 linear comb. θ_1, θ_2 !

MOST GENERAL AXION COUPLINGS

$$\boxed{\mathcal{L}_{4D} \supset \int_{M_4} \theta_1 \,\mathrm{tr}_1 F^2 + \int_{M_4} \theta_2 \,\mathrm{tr}_2 F^2}$$

EMBEDDING THE SM IN $E_8 \times E_8$

@ R^{-1}:

$$\mathcal{L}_{4D} \supset \underbrace{\int_{M_4} \theta_1 \, \mathrm{tr}_1 F^2 + \int_{M_4} \theta_2 \, \mathrm{tr}_2 F^2}_{\text{axion couplings at low-E only depend on how we embed the SM!}}$$

* θ_1, θ_2 : different linear combinations of a & b_i!

E.g.

$$\theta_1 = a + \sum k_i^{(1)} b_i$$

Energy

- ℓ_s^{-1} — S_{10D} — matched unambiguosly
- $\downarrow$
- R^{-1} — $S_{4D}(R^{-1})$
- $\downarrow$ unaffected by running
- EW
- ADMX

OPTIONS

i) $E_8 \supset G \supset SM$; second E_8 "untouched"

ii) SM non-trivially embedded in $E_8 \times E_8$

EMBEDDING THE SM IN $E_8 \times E_8$

$$\mathcal{L}_{4D} \supset \int_{M_4} \theta_1 \, tr_1 F^2 + \int_{M_4} \theta_2 \, tr_2 F^2$$

The same result holds for SO(32)

Hidden sector

$$tr_1 F^2 = \{ QCD + EW + Hypercharge \}$$

Energy

ℓ_s^{-1} — S_{10D} — matched unambiguosly

$\downarrow$

R^{-1} — $S_{4D}\,(R^{-1})$

$\downarrow$

EW — unaffected by running

ADMX

"VISIBLE AXION"

$$\boxed{\theta_1 = a + \sum_i k_i^{(1)} b_i}$$

Model independent axion

value of $k_i^{(1)}$ depends on compact space

model dependent axions

SM EMBEDDING IN A SINGLE E_8

* 4D EFT → @ R^{-1} scale:

SM from first E_8

$$\mathcal{L} = \frac{\theta_1}{8\pi}\left(\alpha_1 B\tilde{B} + \alpha_2 W\tilde{W} + \alpha_3 G\tilde{G}\right) + \underbrace{\frac{\theta_2}{8\pi} H\tilde{H} + \sum_{\text{world-sheet}} V(b_i)}_{\text{axions other than those in } \theta_1\text{, only couple through mixing!}}$$

$$\theta_1 = a + \sum_i k_i^{(1)} b_i$$

* 4D EFT → below EWSB scale:

$$\mathcal{L} = \frac{\theta_1}{8\pi}\left[\alpha_{em}\left(\frac{E}{N} - 1.92\right)F\tilde{F} + G\tilde{G}\right] + V_{eff}(b_i)$$

source of axion mixing!

Only QCD axion to leading order!

↳ Additional axions satisfy:

$$\boxed{\frac{g_{a\gamma}}{m_a} < \frac{\alpha_{em}}{m_\pi f_\pi}}$$

SM EMBEDDING IN A SINGLE E_8

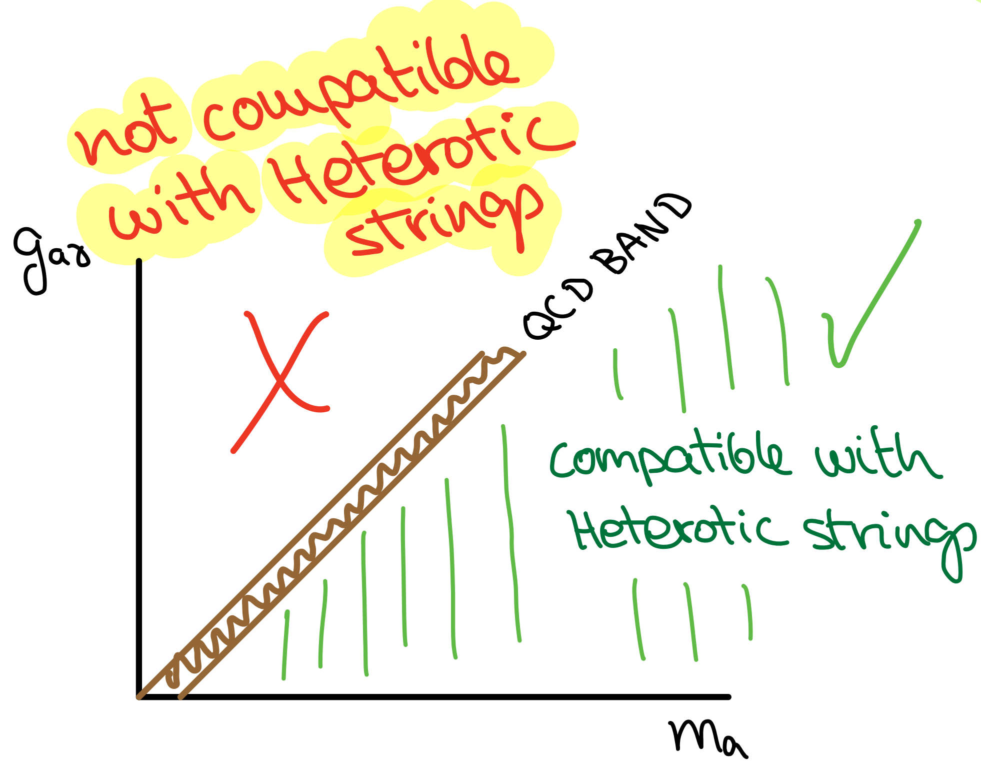
* Find an axion with: $g_{a\gamma}/m_a > \alpha_{em}/m_\pi f_\pi$

For example:

↳ Cosmic birefringence

↳ Ultralight axions coupled to photons

$m_a \sim 10^{-20}$ eV , $f_a \sim 10^{16}$ GeV



Rule out Heterotic Strings ?!

INDEPENDENT OF THE DECAY CONSTANT!

(Embedding into a single E_8)

NON-STANDARD SM EMBEDDING

See orbifold papers:

* Font et al. '90
* Ibañez et al. '87

QCD (part of) EM

$$\mathcal{L}_{4D} \supset \int_{M_4} \theta_1 \,\mathrm{tr}_1 F^2 + \int_{M_4} \theta_2 \,\mathrm{tr}_2 F^2$$

θ_1 ~ QCD axion $\qquad$ θ_2 ~ ALP

* Take: $E_8 \times E_8$

$$[SU(3)\times SU(2) \times U(1)^n] \times [U(1)^m \times G_h]$$

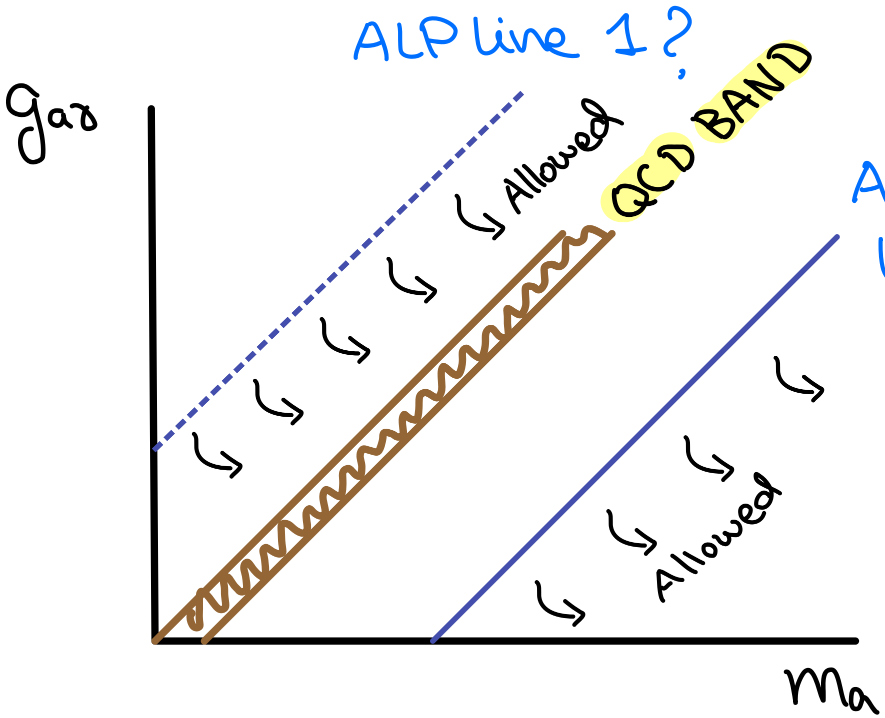
$$SU(3)_c \times SU(2)_L \times U(1)_Y \times G_h^*$$

Keep G_h^* instantons under control! subdominant wrt QCD.

Is there any "realistic" model with non-standard embedding?!

$$\left.\begin{aligned} V(\theta_1) &\simeq -\Lambda_{QCD}^4 \cos\theta_1 \\ V(\theta_2) &\simeq -\Lambda_{ALP}^4 \cos\theta_2 \end{aligned}\right\} \to \quad \Lambda_{ALP} \text{ vs } \Lambda_{QCD} \,?$$

WHAT'S THE "COST" OF THE ALP?



↳ "line" means: $\frac{g_{ALP}}{m_{ALP}} \sim \frac{\alpha_{EM}}{\Lambda_{ALP}^2}$

* ALP line 1 or 2?

Λ_{QCD} vs Λ_{ALP}

↳ Model dependent question!

* Irreducible axion potential

$$V(\theta_{alp}) \sim R^{-4} e^{-2\pi/\alpha_{GUT}} \cos(\theta_{alp})$$

MODEL INDEPENDENT IMPLICATIONS

i) Weak mixing angle is modified: $\sin^2\theta_W < 1/3$!

Standard GUT

$s^2\theta_W = 3/8$

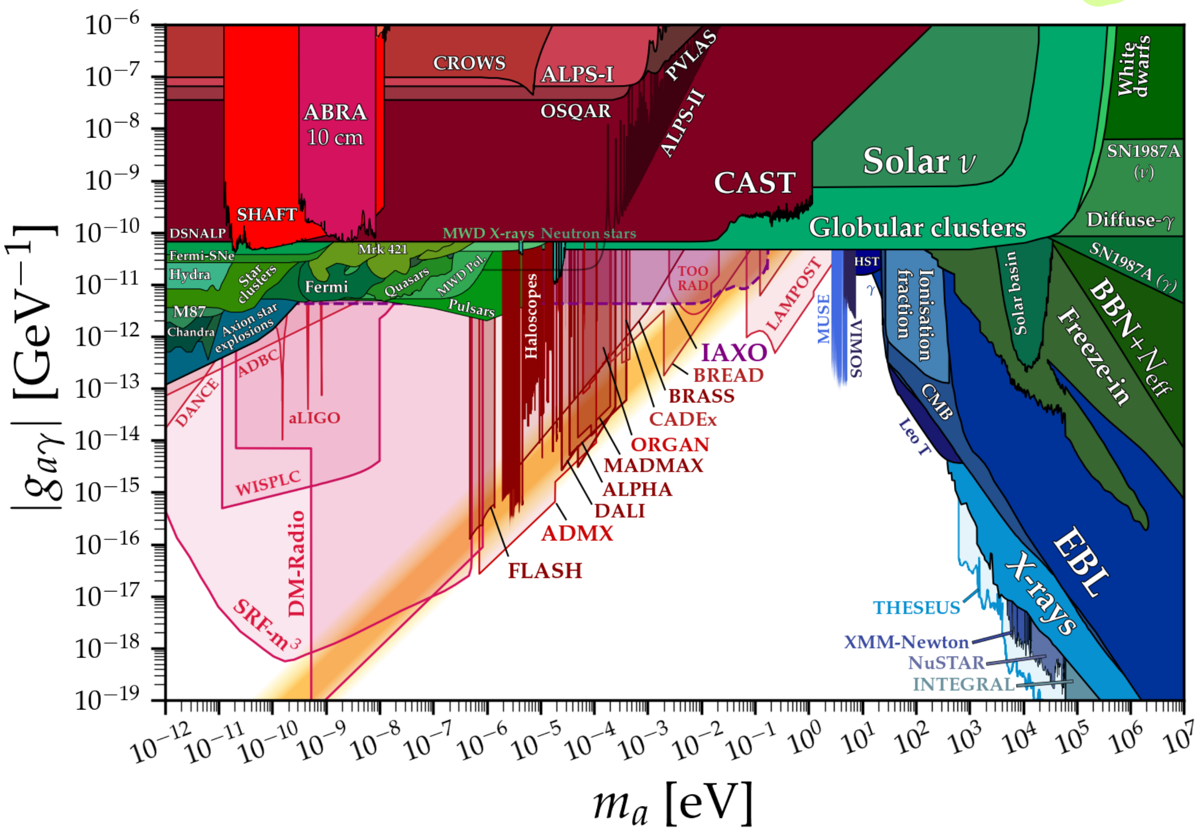
ii) Fractional charges? Possibly chiral!

UV LESSONS FROM IR EXP

Work in progress...

1) On top of Strong CP, Dark Matter, etc axions offer unpolluted UV information: GUTs, Heterotic strings, ... others?

2) Many experiments searching for axion-photon in near future, specially: $g_{a\gamma}/m_a > \alpha_{em}/m_\pi f_\pi$



3) We CANNOT confirm GUTs or Heterotic strings BUT axion searches offer NON-TRIVIAL TESTS of these theories

Back-up

AXIONS AS PROBES OF UNIFICATION

* Starting point: $G_{GUT} \times \prod_i U(1)_{PQ\,i}$

simple gauge group

e.g. $SU(5), SO(10)\ldots$

Set of commuting, global unbroken symmetries

↳ Analogy with SM: $\underbrace{U(1)_B \text{ and } U(1)_L}_{\text{weak interaction } SU(2)}$ →
$\begin{cases} U(1)_{B-L} & \text{anomaly-free} \\ U(1)_{B+L} & \text{ANOMALOUS!} \end{cases}$

applications for baryogenesis etc.

* After symmetry redefinition:

$$G_{GUT} \times U(1)_{PQ} \times \prod_i^{\text{non anom.}} \tilde{U}(1)_i$$

Important !!

$[G_{GUT}]^2 \times U(1)_{PQ} = \mathcal{A} \neq 0$

$[G_{GUT}]^2 \times \tilde{U}(1)_i = 0$

ONLY ONE AXION COUPLED THROUGH THE ANOMALY!

exact or decoupled Goldstone bosons

$\mathcal{A} = 0$

4D GUT: ONE AXION COUPLED TO GAUGE BOSONS

$$\prod_i U(1)_{PQ\,i} \xrightarrow{} \underbrace{U(1)_{PQ}}_{} \times \overset{\text{non-anom}}{\prod_i} \tilde{U}(1)_i$$

field redef.

↳ only this linear combination gives an axion coupled to gauge bosons.

$\mathcal{A}_{PQ} \neq 0$

$\mathcal{A}_i = 0$

and due to quantisation: $\mathcal{A}^{UV} = \mathcal{A}^{IR}$

Above PQ & GUT SSB scales

↳ CURRENTS:

$$\begin{cases} U(1)_{PQ}: & \partial^\mu J_\mu^{PQ} = \mathcal{A}_{PQ} \dfrac{\alpha_{GUT}}{8\pi} \underbrace{G\tilde{G}_{GUT}}_{} \\ \tilde{U}(1)_i: & \partial^\mu J_\mu^{\tilde{U}(1)_i} = 0 \end{cases}$$

↳ This axion couples to both, photons and gluons !!

decoupled Goldstones ! (from gauge bosons)

SINGLE AXION – DEPENDENCE ON PQ SCALE?

PQ current above F_a, M_{GUT}

$$\boxed{\partial^\mu J_\mu^{PQ} = \mathcal{A}_{PQ} \frac{\alpha_{GUT}}{8\pi} G\tilde{G}_{GUT}} \rightarrow$$ What if $F_a < M_{GUT}$!?

A) $F_a > M_{GUT}$: effects of anomaly captured by dim-5 op.

$$\mathcal{A}_{PQ} \frac{a}{F_a} \frac{\alpha_{GUT}}{8\pi} G\tilde{G}_{GUT}$$

axion couples to both photons and gluons!

k_3, k_2, k_1 levels of embedding of $SU(3)$, $SU(2)$, $U(1)$ in G_{GUT}

B) $F_a < M_{GUT}$:

$$\partial^\mu J_\mu^{PQ} = \mathcal{A}_{PQ} \left\{ k_3 \frac{\alpha_3}{8\pi} G\tilde{G}_{QCD} + k_2 \frac{\alpha_2}{8\pi} W\tilde{W} + k_1 \frac{\alpha_1}{8\pi} B\tilde{B} \right\}$$

$\downarrow$ After PQ breaking...

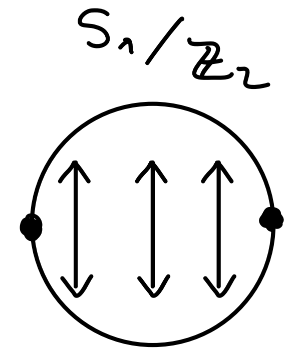
$$\mathcal{A}_{PQ} \frac{a}{F_a} \left\{ k_3 \frac{\alpha_3}{8\pi} G\tilde{G}_{QCD} + k_2 \frac{\alpha_2}{8\pi} W\tilde{W} + k_1 \frac{\alpha_1}{8\pi} B\tilde{B} \right\}$$

$\hookrightarrow$ Again, axion couples to both photons & gluons!

AXIONS FROM HIGHER-D GAUGE FIELDS

↳ Baby version: $QCD \times U(1)_B$ in 5D

"1-form gauge field" ↳ $B_M = (B_\mu, B_5)$



↳ Compactify: $S_1/\mathbb{Z}_2$: $\begin{cases} \text{- gluons: } A_\mu^{a\,(0)} \\ \text{- pseudo-scalar: } B_5^{(0)} \end{cases}$

REMARKS:

i) Chern-Simons couplings $\int K_{cs} \epsilon^{MNPQR} B_M G_{NP} G_{QR} \rightarrow \boxed{B_5^{(0)} G\tilde{G} \text{ in 4D}}$

"cost of moving particle around": $e^{-\int M d\tau}$

ii) Particle worldline Non-local potential $e^{i\theta} = e^{i\int B_5 dx_5}$ ⇝ $V(B_5) = R^{-4} e^{-S} \cos(B_5^{(0)} R)$

$S = 2\pi M R$

~ UV instanton in 4d

AXIONS IN HETEROTIC STRINGS

[see Svrcek, Witten for a review]

SHIFT SYMMETRY BREAKING EFFECTS: [see also Choi 9706171]

* Instantons in $E_8 \times E_8$: additional confining interactions in 4d

* Worldsheet instantons: euclidean closed string worldsheet wrapping 2-cycles

* NS5-branes: non-pert. states (5+1)d, coupled magnetically to B_2
  Can be deformed into UV YM instantons

↳ Only e^{-S} effects, GOOD QUALITY AXIONS!

MATCHING AXION COUPLINGS

* Take 10d SUGRA action:

Green-Schwarz mech.

$$S_{10d} \supset \int_{X_6} B_6 \wedge \left[\mathrm{tr}_1 F^2 + \mathrm{tr}_2 F^2 \right] + \int_{X_6} B_2 \wedge X_8^{(YM)}$$

↳ Contains: $\mathrm{tr}_i F^2 \, \mathrm{tr}_j F^2 , \ldots$

MI axion couplings

MD axion couplings

e.g. $K_i = \int B_2 \wedge \mathrm{tr}_i F^2 \rightarrow$ quantised

* Consistency of the 10d SUGRA gives couplings of B_2 and B_6 to gauge bosons.

$$\boxed{S_{10d} \longleftrightarrow \text{Axion couplings @ } R^{-1} \text{ in 4d EFT}}$$

MATCHING AXION COUPLINGS

* MI axion couplings (a): $\mathcal{L}^{4d}_{MI} = a/f_a \left(\mathrm{tr}_1 F^2 + \mathrm{tr}_2 F^2 \right)$ universally coupled to gauge bosons

$\mathrm{tr}_1 F^2 = \sum_i \mathrm{tr}\, F_i^2 \leftarrow$ unbroken 4d gauge groups from 1st E_8

b_i couples to "entire" $\mathrm{tr}_i F^2$!

* MD axion couplings (b_i): $\mathcal{L}^{4d}_{MD} = \sum k_i^{(1)} b_i \mathrm{tr}_1 F^2 + \sum k_i^{(2)} b_i \mathrm{tr}_2 F^2$

depend on compact space
CALCULABLE!

MOST GENERAL AXION COUPLINGS

$$\boxed{\mathcal{L}_{4D} \supset \int_{M_4} \theta_1 \mathrm{tr}_1 F^2 + \int_{M_4} \theta_2 \mathrm{tr}_2 F^2}$$

NON-STANDARD SM EMBEDDING

QCD $\qquad\qquad$ (part of) EM

$$\mathcal{L}_{4D} \supset \int_{M_4} \theta_1 \, \mathrm{tr}_1 F^2 + \int_{M_4} \theta_2 \, \mathrm{tr}_2 F^2$$

$\sim$ QCD axion $\qquad\qquad$ $\sim$ ALP

* Take: $E_8 \times E_8$

$$[SU(3)\times SU(2) \times U(1)^n] \times [U(1)^m \times G_h]$$

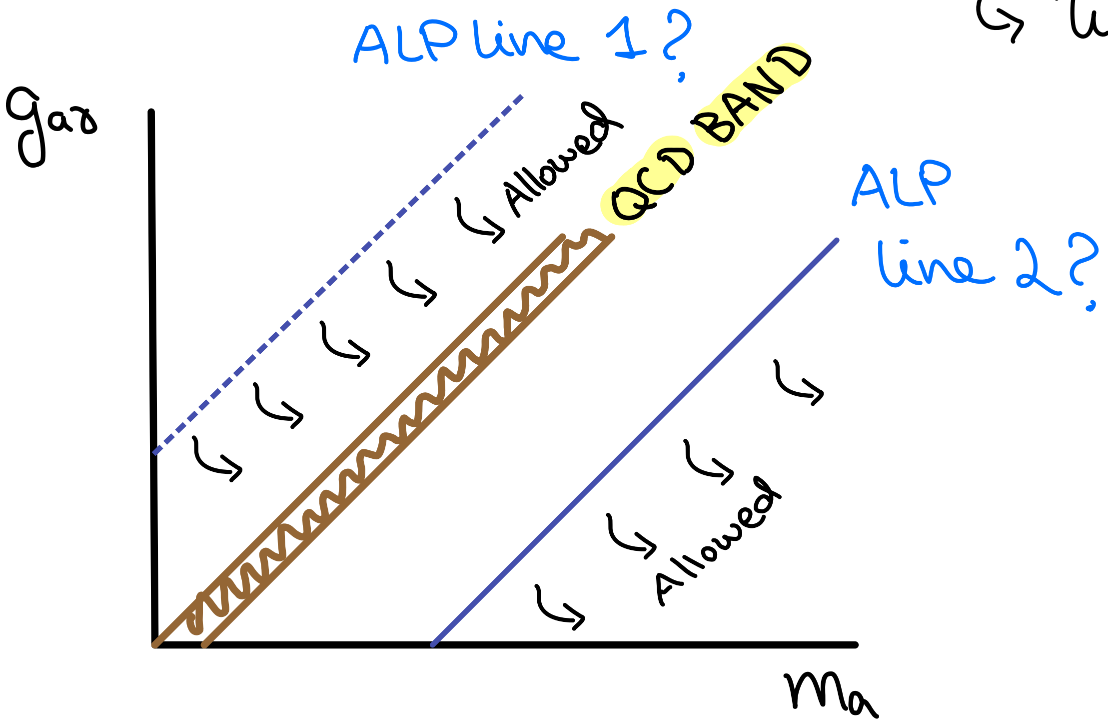
May arise in orbifold compactifications

$$\underbrace{SU(3)\times SU(2)}_{} \to SU(3)_c \times SU(2)_L \times U(1)_Y \times G_h^*$$

Keep G_h^* instantons under control! subdominant wrt QCD.

$$\left.\begin{aligned} V(\theta_1) &\simeq -\Lambda_{QCD}^4 \cos\theta_1 \\ V(\theta_2) &\simeq -\Lambda_{ALP}^4 \cos\theta_2 \end{aligned}\right\} \to \quad \Lambda_{ALP} \text{ vs } \Lambda_{QCD} \,?$$

WHAT'S THE "COST" OF THE ALP?



↳ "line" means: $\frac{g_{ALP}}{m_{ALP}} \sim \frac{\alpha_{EM}}{\Lambda^2_{ALP}}$

* ALP line 1 or 2?

Λ_{QCD} vs Λ_{ALP}

↳ Model dependent question!

* Irreducible axion potential

$$V(\theta_{alp}) \sim R^{-4} e^{-2\pi/\alpha_{GUT}} \cos(\theta_{alp})$$

MODEL INDEPENDENT IMPLICATIONS

i) Weak mixing angle is modified: $\sin^2\theta_W < 1/3$!

Standard GUT

$s^2\theta_W = 3/8$

ii) Fractional charges? Possibly chiral!

FIELD THEORETIC AXIONS?

* Can we get axions from the phase of complex scalars?

$$\phi = \overline{\Phi}\, e^{ic} \quad ; \quad c \to c + q_c \theta$$

YES! BUT only in theories where the lightness is guaranteed by a gauge symmetry: $U(1)_A$

See: Anomalous U(1) scenario

$$\mathcal{O} \sim \underbrace{e^{-S} e^{ia} \phi^{\nu}}$$

phase from ϕ mixes with "a" and inherits axion coupling

$$\frac{c}{f_{eff}} F\tilde{F}$$

↳ Couplings of "c" are the same as MI axion, "a"!

* QUESTION: Can we form cosmic strings?
Do they have "de-compactified" core?

COMPUTING $K_{1,2}^{(i)}$

* $K_{1,2}^{(i)}$ are "anomaly coeff." for model dependent axions.

$$\int B \wedge X_8 = \sum_i K_1^i \int_{M_4} b_i \, \mathrm{tr}_1 F^2 + \sum_i K_1^i \int_{M_4} b_i \, \mathrm{tr}_2 F^2$$

$$K_1^{(i)} = \int_{\Sigma_6} \beta_i \wedge \left(-\mathrm{tr}\, R^2 + 2\mathrm{tr}_1 F^2 - \mathrm{tr}_2 F^2\right)$$

Field strength subject to topological constrain:

$$dH = -\mathrm{tr}_1 F^2 - \mathrm{tr}_2 F^2 + \mathrm{tr}\, R^2 \longrightarrow [\mathrm{tr} R^2] = [\mathrm{tr}_1 F]^2 + [\mathrm{tr}_2 F]^2$$

same cohomology class

TWISTED STATE CONTRIBUTIONS

* Compactification on non-simply connected manifold

$$K = K_0 / G$$

↳ Fractionally charged states appear! ⇝ Do they modify $g_{a\gamma}/m_a < \alpha_{em}/m_\pi f_\pi$?

↳ ψ, do they induce $g_{a\gamma}$?

* EFT

$z := \mu / m_\psi$

$$\mathcal{L} = -\mu \bar{\Psi} e^{i\gamma_5 a} \psi - m_\psi \bar{\Psi} \Psi \longrightarrow g_{a\gamma} \sim \frac{\alpha_{em}}{f_a} z$$

↳ Calabi-Yau compactification: $z = e^{-S}$; $S \sim 2\pi/\alpha$

↳ Orbifold: $z = \dfrac{m_a}{m_\psi} e^{-S/2}$

P - FORM FIELDS

* Antisym. tensor field (~ generalised gauge potential)

$$C_{p+1} \to C_{p+1} + d\Lambda_p$$

p. form gauge parameter

* Field strength: $F_{p+2} = dC_{p+1}$

* p-branes = electric objects $\longleftrightarrow$ $S_{elec} = Q \int_{W_{p+1}} C_{p+1}$

* Duals:

↳ $F_{p+2} = F_{d-p-2} \longleftrightarrow F_{d-p-2} = dC_{d-p-3}$

↳ $(d-p-4)$-branes electrically charged under C_{d-p-3}

and magnetically charged under C_{p+1}.

Axions in Heterotic Strings

If time allows...

MD axions $\quad b_i = \int_{w_i} B_2$

MI axion $\quad a = \int_{X_6} B_6$

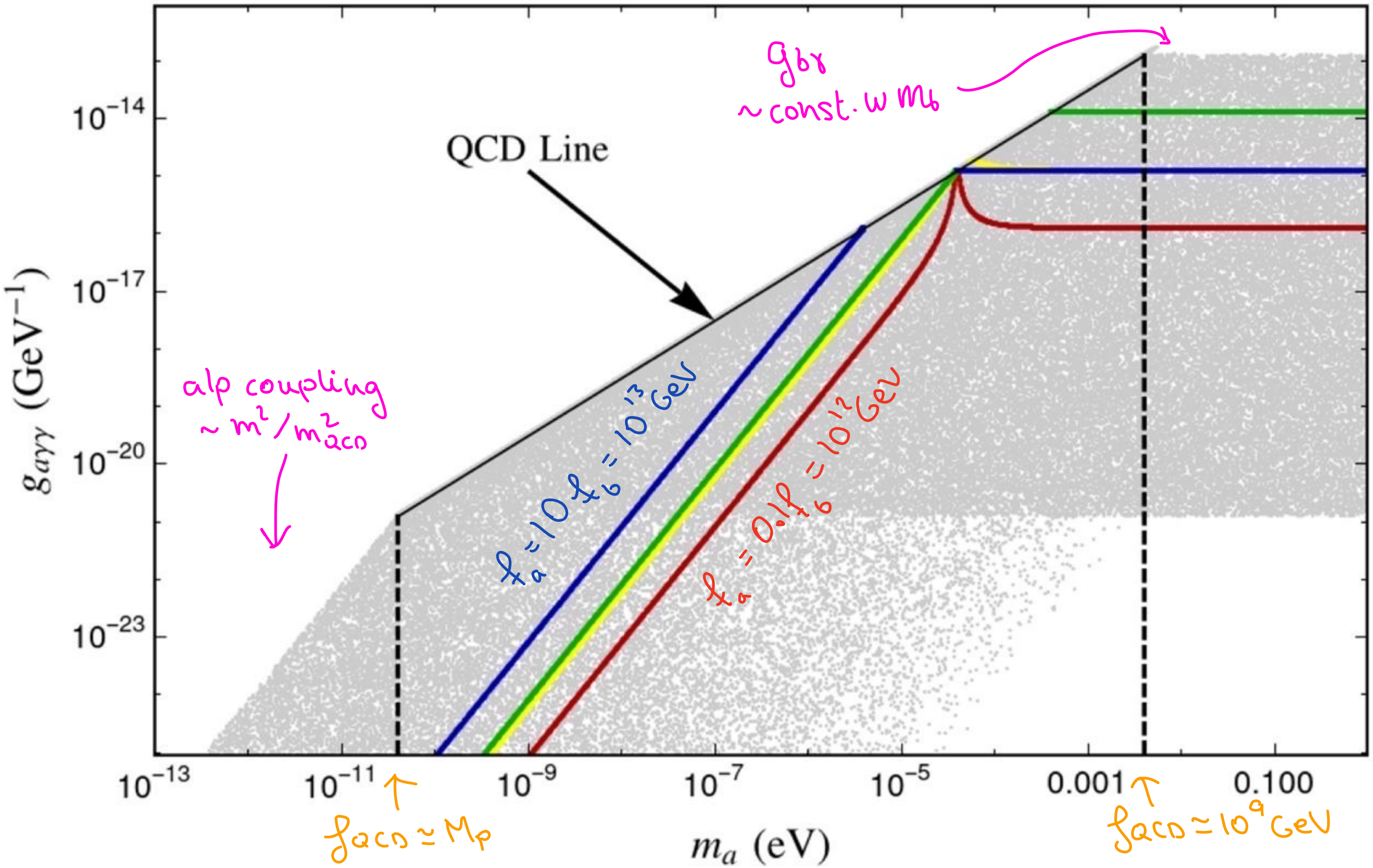
$$\begin{tikzcd}
B_2 \arrow[rr, leftrightarrow, "\text{10D dual object}"] \arrow[d, leftrightarrow, "\text{electrically charged under...}"'] \arrow[drr, leftrightarrow] & & B_6 \arrow[d, leftrightarrow, "\text{electrically charged under...}"] \arrow[dll, leftrightarrow, "\text{magnetically charged}"'] \\
\text{superstring} & & \text{NS5-branes}
\end{tikzcd}$$

↳ 4D point of view, superstring ≡ axion string!

ALP-photon coupling via mixing

$$\mathcal{L} = \left(\frac{a}{f_a} + \frac{b}{f_b}\right) G\tilde{G} + \frac{1}{2} m_b^2 b^2$$

Generate sets of "points" $(a, g_{a\gamma}) + (b, g_{b\gamma})$



Ranges:

- $m_b = [10^{-11}, 1]$ eV
- $f_a, f_b = [10^9, 10^{18}]$ GeV

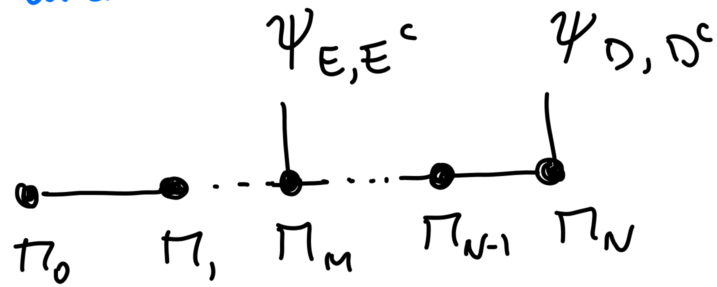
ADDITIONAL ALPs: $\frac{g^{\gamma}_{alp}}{m_{alp}}$ is always smaller than QCD axion $\frac{g_{a\gamma}}{m_{QCD}}$

[Does not depend on number of axions]

Clockwork axions

- Each site ≡ scalar field
- links ≡ nearest neighbor interact.

[1611.09855]



↳ Crucially relies on having "incomplete" multiplets @ each site.

* coupling to photons gets exp. enhancement

$$g_{a\gamma} \simeq \frac{\alpha_{em}}{F_a}\left(E/N - 1.92\right)$$

with $E/N = q^{N-M}$

↳ GUT-like constructions are expected to get back to $\frac{E}{N} = \frac{k_1 + k_2}{k_3}$

$\mathcal{N}$ mirror sectors?

See 1802.10093, 2102.00012

$$\mathbb{Z}_N : SM_k \longrightarrow SM_{k+1}$$
$$a \longrightarrow a + \frac{2\pi k}{N} f_a$$

$\mathcal{N}$ copies of SM

$$m^2 \sim m_{QCD}^2 \times \frac{1}{2^N}$$

E.g. to get $m \sim 10^{-22}\,\text{eV}$; $F_a \sim 10^{17}\,\text{GeV}$

Need: $\mathcal{N} \sim 100$ copies of SM

FLIPPED GUTS

* QUANTUM NUMBERS

$$SU(5) \times U(1)_X$$

$$\underbrace{5_{-3},\ 10_1,\ 1_5}_{\text{SM family} + \nu_R}$$

* WEAK MIXING ANGLE

$$\sin^2\theta_w = \frac{3/8}{1 + \frac{5}{3}\left(\frac{\alpha_5}{\alpha_X} - 1\right)}$$

↳ Axion coupled to $U(1)_X$ without $SU(5)$ → $\nexists$ common origin

↓

$\alpha_5 \neq \alpha_X$

←

i) $\nexists$ reason for SM charges

eg: fermion with electric charge $+\frac{1}{2}$?

ii) $\nexists$ prediction of $\sin^2\theta_w$!

↑ price to pay... :(

Kinetically Mixed Photons ?

* $G_{GUT} \times U(1)_{Dark}$ with 2 axions:

dark photon

QCD axion

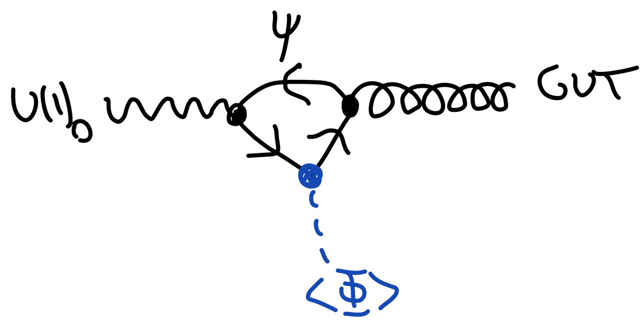
axion coupled to dark sector

$$\alpha_{GUT} \frac{a}{f_a} G\tilde{G}_{GUT} + \frac{\alpha_D}{f_b} b_D F\tilde{F}_D$$

* Gauge invariance forbids tree-level kin. mixing

↳ higher dim: $\frac{1}{M_P} F_D \, \Phi \, G_{GUT}$

$$\epsilon \sim \frac{\alpha_{GUT}\alpha_D}{16\pi^2} \frac{M_{GUT}}{M_{Pl}}$$



* After GUT SSB: $\frac{\epsilon^2}{8\pi} \alpha_D \frac{b}{f_b} F\tilde{F}$

expected to give a large suppression!

$\epsilon^2 \lesssim 10^{-8}$